Managing flow ramping operations at run-of-river hydroelectric projects

By
Adam Lewis, M.Sc. R.P. Bio., Ecofish Research Ltd., Canada, and
Katie Healey, M.Sc., Ecofish Research Ltd., Canada

ABSTRACT

Run-of-river projects are promoted as a more sustainable alternative to traditional storage projects because they don't alter the flow regime in downstream reaches. Although true run-of-river operations follow the daily flow regime, they can cause rapid short-term changes to streamflow of sufficient magnitude to dewater habitat and strand fish. In this paper we examine how run-of-river projects affect the short-term temporal and spatial pattern of flow change and identify the factors influencing fish stranding at these projects.

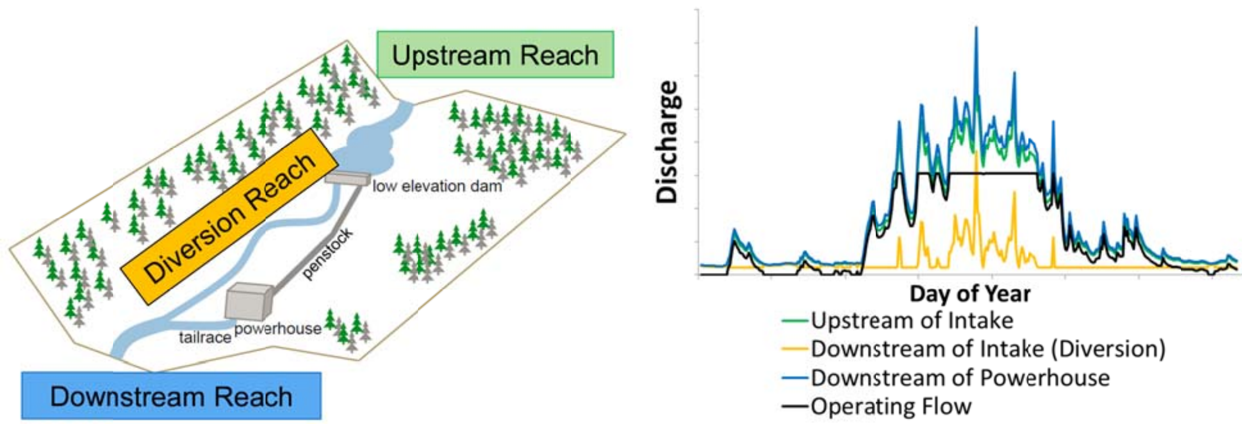
Although many new run-of-river projects in British Columbia are located on non-fish bearing streams, they affect flows downstream in waters inhabited by salmon and trout. Guidance on managing ramping and stranding effects on these projects is lacking in the literature, which focusses on storage projects, where flow releases are reliably delivered from reservoir storage. Run-of-river projects lack the storage necessary to offset utility disconnection events, which can suddenly decrease streamflow, stranding substantial numbers of fish.

In British Columbia utilities and regulators have identified specific operating and environmental conditions where juvenile fish stranding is likely, supporting a risk-based approach to setting, managing, and implementing ramping rate mitigation. Stranding risks vary between habitats of different gradients and channel morphologies, and habitats immediately downstream of projects are at highest risk, although risk remains high for dozens of kilometres downstream on some projects. This work demonstrates the value of season-specific ramping rates, to mitigate high stranding risk during the spring. Using new information gained from the monitoring of these projects in British Columbia, we describe a management approach to increase operational efficiency while better avoiding fish mortality from stranding.

Background

An increase in run-of-river hydropower development in British Columbia in the past decade has heightened interest in the effects of these projects on aquatic habitat. Run-of-river hydropower has the potential to create less environmental impact than traditional storage facilities, as the flow regime downstream of the powerhouse remains unchanged (Figure 1). Although this premise is true on a daily basis, in practise run-of-river projects do affect the short-term flow regime by changing the rate of change of flow (the ramping rate). As run-of-river projects are typically sized at or well above the average annual flow, changes in operating flows can be large enough to dewater large areas of habitat, stranding and killing fish. The effects of flow ramping are generally well-known (e.g. Cushman 1985; Hunter 1992), however they have not been extensively studied at run-of-river projects, and the factors influencing fish stranding are complex (Irvine *et al.* 2015).

Figure 1. Configuration (adapted from Connors *et al*. 2014) and flow regime of a run-of-river hydroelectric facility



Project Layout

A typical run-of-the-river hydroelectric project consists of a diversion intake weir, a penstock or tunnel, and a powerhouse. Although ‘run-of-river’ operations are followed at large hydroelectric projects with major dams that impound substantial reservoirs, in the modern format a run-of-river project typically has a weir of 2 m to 8 m height and impounds a headpond of only a few hundred meters length. The potential energy for this modern format is provided by the difference in elevation between the intake and the powerhouse, leading developers to build penstocks/tunnels several kilometres long, creating substantial diversion reaches watered by an instream flow release from the intake.

Flow Hydrology and Ramping and Hydrology

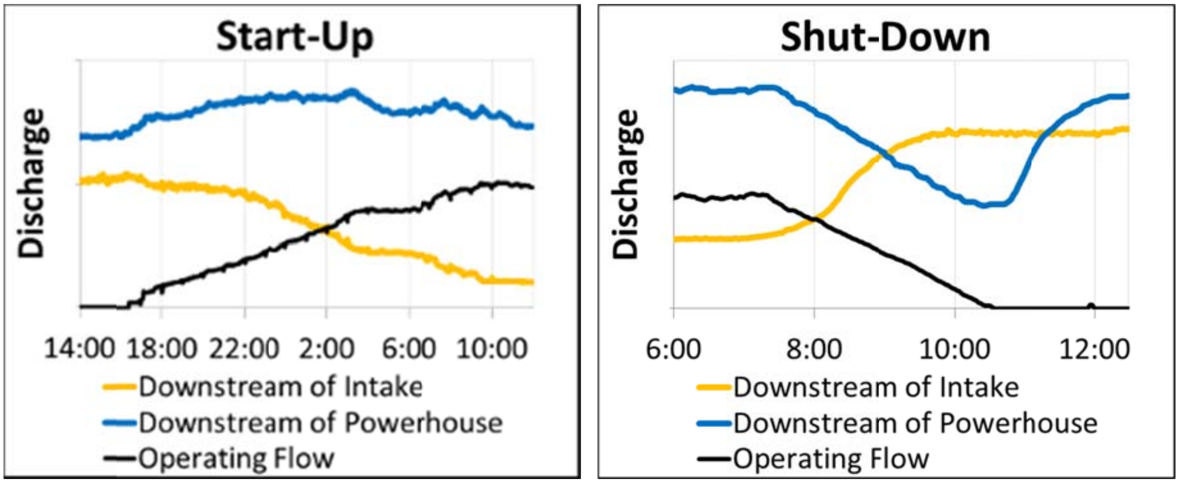
Hydroelectric operations at run-of-river projects continuously adjust electrical generation to match the volume of inflow into the headpond. Whenever electrical generation changes, the volume of flow released from the powerhouse changes, with corresponding but opposite changes in flow in the diversion and downstream reaches. Changes in flow rate are referred to as flow ramping, which is defined as the "gradual or progressive alteration of discharge in a stream channel resulting from the operation of a hydroelectric facility". Ramping rate is the rate of change of stage (and/or discharge) per unit time, typically measured and expressed in units of in/hr or cm/hr.

When generation increases at a run-of-river project, flow released through the powerhouse increase proportionally, but there is an equivalent decrease of flow in the diversion reach (Figure 2a). The increase of flow downstream of the tailrace is temporary, lasting only until reduction in diversion reach flow arrives at the powerhouse. Conversely, when flows are decreased through the powerhouse, flow in the downstream reach is temporarily reduced, while an equivalent volume of flow is spilled from the intake, increasing flows in the diversion reach (Figure 2b). Flow returns to natural levels in the downstream reach, but only after the increased flow spilled from the intake has arrived at the powerhouse. The hydraulic connection between the intake and the powerhouse, combined with the absence of flow storage, causes upramping at one location (diversion or downstream) to be proportional to downramping at the other such that upramping rates are constrained by downramping rates. The 'lag time' between start-up/shut-down and the return to natural flow in the downstream reach is determined by the travel time of flow through the diversion reach, which in turn depends on the length, gradient, and roughness of the diversion reach.

Most monitoring effort at run-of-river projects has focused on the effects of downramping (decreases in flow), because upramping (increases in flow) does not dewater fish, though it can displace fish to downstream habitats.

Figure 2. Flow in the diversion reach (downstream of intake) and downstream reach during a) project start-up and b) project shut-down

a) Start-up b) shut-down



Stranding

Rapid flow reductions can lead to fish stranding stranded in the interstices on gravel or cobble banks or bars, leading to mortality from suffocation, desiccation, freezing, or predation (Irvine *et al.* 2015). Fish may be isolated in pools that remain after discharge reductions or subsequently dewater. This can lead to mortality from suffocation, desiccation, freezing, or predation of fish present, violating regulatory requirements. Mortality following dewatering events has been reported for juvenile salmonids in as little as 10 minutes (Saltveit *et al.* 2001, Hunter 1992). Even if the flow changes are not drastic enough to kill fish, they can interrupt feeding, migration, and spawning behaviours, causing fish to migrate from preferred habitats, and effectively reducing the value of these habitats (Nagrodski *et al.* 2012).

Various biological and physical factors affect fish stranding risk. Physical factors include ramping rate, distance downstream of the facility, season, time of day, substrate type, channel slope, and wetted history (how long the habitat was wetted prior to the event). Flow level strongly influences stranding risk, with low flow levels posing a greater risk of fish stranding (stranding sensitive habitats are largely wetted at high flows). Biological factors influencing stranding risk are primarily fish behaviour and life stage, with species composition and density also playing a role (Nagrodski *et al.* 2012).

The extent of fish stranding varies between diversion and downstream reaches. Fish stranding risk is higher in downstream reaches because of the gentler channel slope.

Furthermore, downstream reaches support higher densities of fish because they are of lower gradient, more accessible, and provide higher quality habitat that is preferred by the small life stages that are at greater risk of stranding. Fish stranding has been observed in diversion reaches, but at lower magnitude and less frequently.

Mitigation

Fish stranding is avoided at hydroelectric projects by controlling and limiting the rate of flow change at the powerhouse and accordingly the rate of stage change in downstream habitats sensitive to dewatering. Under ideal operating conditions, run-of-river projects continuously and precisely match powerhouse outflows to headpond inflows, avoiding changes in the natural ramping rate. In practise however, projects must rapidly shut-down in response to electric grid demand, transmission line trips, electrical and mechanical faults, operator errors, and software bugs. Although full bypass valves can avoid shut-downs altogether, operators typically often rely on the turbines to manage flow ramping. Regardless of how flows are controlled, flow ramping must be managed to follow specific ramping rates designed to avoid fish stranding.

Regulatory and utility biologists have long advocated for ramping rate limitations to protect fish from stranding. In British Columbia generic standard ramping rates are 2.5 cm/hr when fry are present and 5.0 cm/hr at all other times, although no ramping may be allowed under some conditions (Table 1, Cathcart 2005). Full shut-down at these ramping rates can require more than ten hours to achieve, which although reasonable in the context of a seasonal flow regime change at a major storage project, impairs generating efficiency at run-of-river hydroelectric plants.

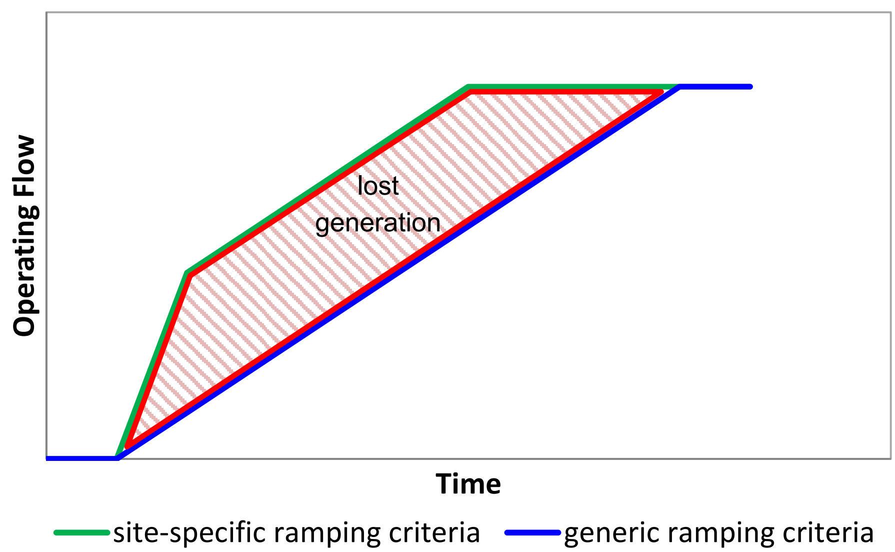
Run-of-river projects following the generic standard ramping rates require hours to start-up, which can affect generation by delaying the time to reach full operating load (Figure 3). Similarly, these rates prolong shut-down, which can increase wear on mechanical equipment and increase the risk of malfunctions. Project operators generally seek to shut-down and start-up as quickly as possible. The generic standard ramping rates are not considered adequate at many projects, and cannot be achieved at some older projects where the mechanical and electrical equipment has limited flow ramping capabilities.

The generic standards identified by DFO ranged from 0 cm/hr to 10 cm/hr, depending on season (time of year and life stage history which were deemed equivalent) and time of day (day or night). Although these rates are arguably protective of fish as they inferred no flow ramping in some conditions, their utility for adoption at run-of-river projects was limited, given that natural flows are constantly changing and therefore exhibiting non-zero rates of change. As generic criteria these rates are protective from a regulatory perspective but stringent from an operating perspective. To better manage ramping operations, development of site specific ramping rate criteria is critical.

Table 1. DFO Generic Standard Ramping Rates (Table 6.1 Cathcart 2005).

Time of Year	Life Stage History	Day Ramp Rate	Night Ramp Rate
April 1 - July 31	Fry Emergence	0 - 2.5 cm/hr	2.5 - 5 cm/hr
July 31 - October 31	Rearing until temp < 5°C	0 - 2.5 cm/hr	5 - 10 cm/hr
November 1 - April 1	Winter Rearing	0 cm/hr	0 - 5 cm/hr

Figure 3. Illustration of potential loss in generation caused by delayed start-up to meet flow ramping rates.



The literature reports that slow ramping rates avoid fish stranding. However, the results are inconsistent, and a recent major study found that the rate of ramping was unrelated to fish stranding, although the magnitude of stage change was strongly related (Irvine *et al.* 2015). Large reductions in stage strand fish, regardless of the rate of ramping. This has been observed at storage projects, run-of-river projects, and in natural rivers where prolonged seasonal recessions in flow isolate and dewater habitats. Limiting rates of flow ramping may effectively mitigate fish stranding at hydroelectric projects, but is not universally effective and cannot eliminate fish stranding. Developing effective flow ramping rates that can increase operational efficiency requires site-specific hydrological and biological information collected over a range of conditions applied in consideration of seasonal variation in these factors.

New Findings from British Columbia

The rapid growth in run-of-river development in the mid-2000s led the provincial and federal governments in Canada to require ongoing monitoring of the effects of on aquatic habitats (Hatfield *et al.* 2007). Flow ramping was not a key focus of the first few years of monitoring, but rapidly gained attention for the regulators as stranding events were reported in the media. The guidelines required operational plans that describe the parameters and criteria for flow ramping rates developed following a regulatory guideline (Cathcart 2005) and real-time monitoring of project ramping operations.

Monitoring results from dozens of run-of-river projects over since 2007 have provided important new information to inform the management of flow ramping. The key findings are as follows:

1. Most projects are able to meet the generic ramping rate criteria of -2.5/-5.0 cm/hr. Non-compliances are not common, based on tens of thousands of operating hours of monitoring. However, small fish kills have been observed at some projects, and large fish kills have been observed at a few projects.
2. Some projects struggle to meet the generic ramping rate criteria, typically because they were not designed to do so. In these cases retrofits have been successful in meeting target ramping rates.
3. Fish stranding is predictably observed in the same habitats, year after year, allowing monitoring effort to be targeted and optimized. Shallow, gently sloped shorelines with large substrate and uneven bed topography create the highest risk of fish stranding.
4. Season strongly influences the risk of fish stranding by influencing fish behaviour. The use of deeper habitats in the fall and winter periods limits the risk of fish stranding, while warmer conditions in summer promote high fish mobility, limiting the occupancy of shallow habitats. Spring, when juvenile salmon emerge and inhabit shallow habitats prone to dewatering, and water temperatures limit movement, is the period of highest risk.
5. The generic standard rates have proven effective at avoiding fish stranding, particularly where fish are stranded by beaching in the substrate interstices. However, generic standard rates, (and in some cases, all ramping rates) have been less successful at the stranding of fish in shallow depressions along stream margins.

6. More rapid ramping rates have been achieved at some projects through ongoing testing and monitoring of ramping rates. Few projects have pursued ramping rates in excess of the generic ramping rate criteria, however, where warranted, project operators have diligently pursued extensive monitoring and testing that has demonstrated higher ramping rates can also limit fish stranding risk.
7. Natural fish stranding is extensive and commonly observed at run-of-river projects.
8. The timing of sensitive seasons varies between stream and species. Site specific information is required to adjust the project ramping schedule if ramping rates are going to be increased above the generic standard rates.

These new findings are being added to on a monthly basis as new projects are commissioned and studies on existing projects are completed. This information has informed an approach to the management of flow ramping at hydroelectric projects focussed on site-specific physical and biological factors that can be readily and accurately measured and which have a strong causal link to fish stranding.

Ramping Management Approach

The rapid growth in run-of-river development has led the provincial and federal governments in Canada to develop monitoring protocols specific to flow ramping (Lewis *et al.* 2011). The primary purpose of data collection through this standardized monitoring is to detect ramping events and determine if fish have been stranded. In addition, ramping monitoring data can also be used in an adaptive management approach, allowing for improved flow management at individual facilities. Typically the focus is to increase ramping rates to increase operational efficiency at hydroelectric projects while still protecting against fish stranding. However, for streams with highly sensitive habitats, the generic standard rates may be required to avoid fish stranding, with even these rates posing a risk of fish stranding in highly sensitive habitats.

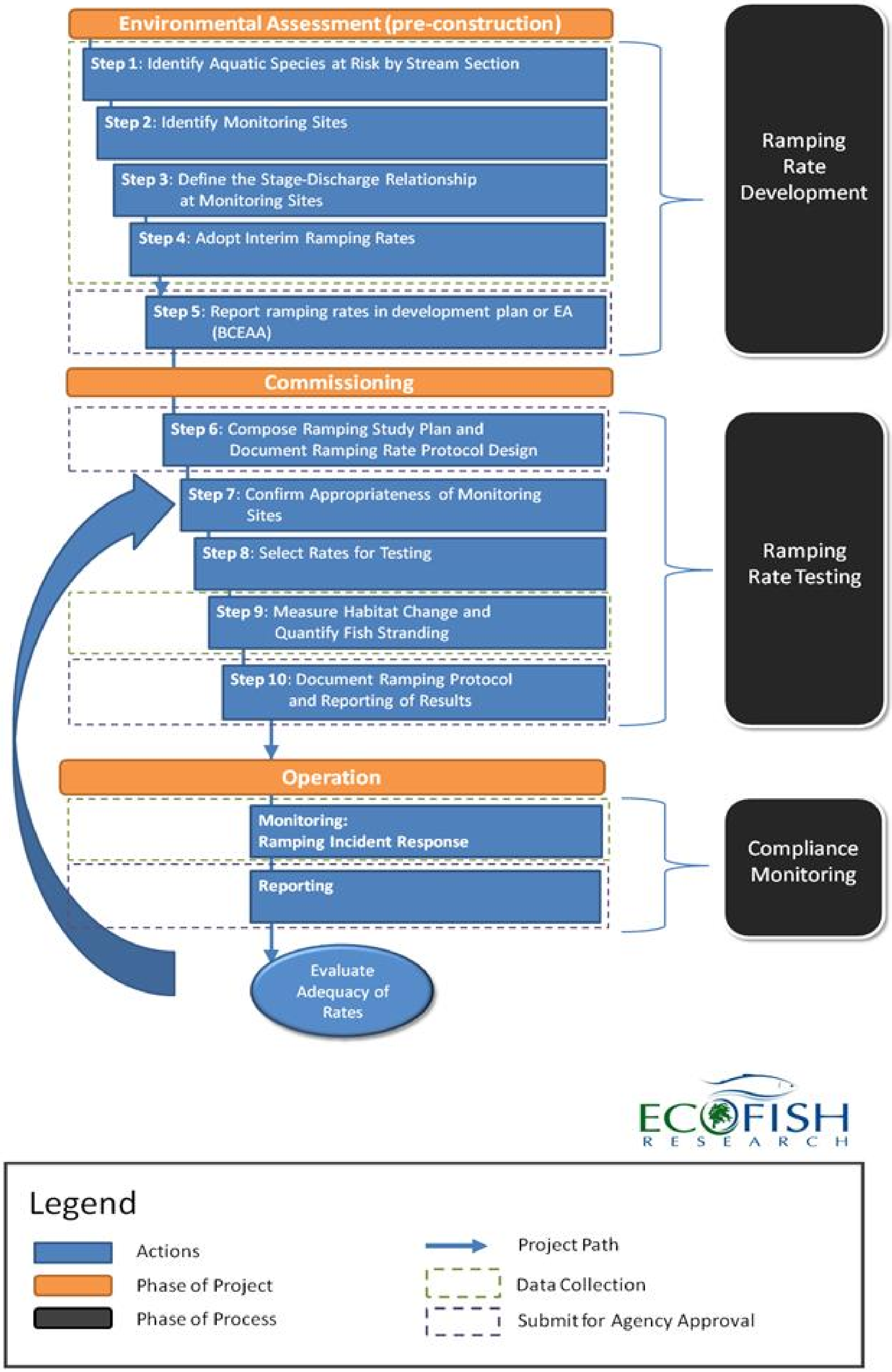
Monitoring data from run-of-river hydroelectric facilities in BC has allowed refinement in the approach to fine-tuning ramping rates. The process of developing stream-specific ramping rates, testing their effectiveness on the stream of interest, and monitoring compliance consists of three distinct, consecutive phases aligned with the development of hydroelectric projects. In the environment assessment phase, coincident with the environmental assessment, background data on projects is obtained and evaluated to help define ramping rates. In the testing phase interim ramping rates are implemented and tested on the stream of interest during the commissioning of the project. In the compliance monitoring phase, adherence to the ramping rates is continuously monitored, and rates can be adjusted and further tested to refine flow ramping management. A schematic of the process of designing, testing and monitoring compliance of flow ramping rates is provided in Figure 1. This approach builds upon a 9-step protocol to derive ramping rates developed by DFO (Cathcart 2005).

The three key pieces of information needed to begin analysis during the environmental assessment process are the locations of critical sites, what fish species are at risk of stranding at these sites, and the relationship between water level and discharge at the sites. On site testing of hydrology is typically conducted prior to commissioning to provide guidance on equipment control selection. During commissioning, additional ramping testing allows the measurement of lag time in the diversion reach and the extent of channel attenuation, data which allow real time operations to take advantage of natural flow pulses to moderate ramping events caused by project operations. In some cases natural flow change rates provide a context for setting project specific ramping rates, however, natural downramping rates are typically slower than the generic standards, particularly at the lower flow levels when stranding risk is elevated.

Interim standards can be derived for projects prior to commissioning, but typically are confirmed during commissioning. More accurate data on ramping rates and the response to project operations can be gathered during equipment testing, or stand-alone tests dedicated to ramping monitoring during commissioning. The testing of ramping rates can be accompanied by searching for stranded fish following a simple but routinized protocol (Lewis *et al.* 2011, 2013).

During project operations ongoing monitoring allows ramping rates to be monitored for compliance. Searches for stranded fish are implemented based on this monitoring. The resultant monitoring results allow the effectiveness of the interim rates to be evaluated by responding to and searching minor events at rates slightly above the interim rates. The results of responses to substantial non-compliances meet the regulatory obligation but have additional value as passive tests of higher rates. Combined with an active adaptive management of target ramping rates at suspected thresholds of ramping tolerance, this monitoring can provide convincing data on the effectiveness of the rates.

Figure 4. Schematic of the Flow Ramping Rate Development, Testing, and Compliance Monitoring Process



Conclusions

The development and testing of flow ramping rates at many projects in British Columbia has allowed the confirmation of standard generic rates as protective of fish from flow ramping events. Monitoring has provided clear generalizable findings, but also identified considerable variance between projects. The methods identified in the draft "Long-term Monitoring Guidelines for New and Upgraded Hydroelectric Projects in British Columbia and Yukon Territory" and current ramping guidelines build on earlier studies of flow ramping rates for hydropower developments that recommended the development of a ramping rate derivation protocols for run-of-river hydroelectric developments in BC (Cathcart 2005). Ongoing application of these methods is expected to further resolve uncertainties over the effectiveness of flow ramping at run-of-river projects and lead to more effective protection, while permitting more efficient project operations.

Authors

Adam Lewis, M.Sc. R.P. Bio. is a Fisheries Biologist and founder of Ecofish Research Ltd. He has co-authored numerous provincial and federal guidance documents related to environmental assessment and monitoring at run-of-river hydropower facilities, including the provincial methods for monitoring flow ramping effects.

Katie Healey, M.Sc. is a Senior Analyst at Ecofish Research Ltd. She has led the development of ramping monitoring analytical approaches at run-of-river hydropower facilities, and evaluated the results of ramping tests to develop site specific ramping rates at numerous projects.

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